Deep Tillage and Crop Rotation Effects on Cotton, Soybean, and Grain Sorghum on Clayey Soils

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ABSTRACT

Deep tillage (subsoiling) of clayey soils in the fall when the profile is dry is a new concept that results in increased yields and net returns from soybean [*Glycine max* (L). Merr.] grown without irrigation. Crop rotation may also result in increased crop yields. Field studies were conducted on Tunica clay (clayey over loamy, smectitic, nonacid, thermic, Vertic Haplaquept) near Stoneville, MS (33°26′ N lat) to determine the individual and combined effects of fall deep tillage and crop rotations on crop yields and net returns. Treatments included monocrop cotton [*Gossypium hirsutum* (L.)], soybean, and grain sorghum [*Sorghum bicolor* (L.) Moench], and biennial rotations of cotton with grain sorghum and soybean with grain sorghum grown without irrigation and in either a conventional-till (CT) or deep-till (DT) production system. Yields from all cotton and soybean crop sequences grown in the DT respectively averaged 541 kg ha^{-1} and 525 kg ha^{-1} greater than comparable cotton (2184 kg ha^{-1}) and soybean (2983 kg ha^{-1}) crop sequences grown in the CT. Net returns from monocrop cotton (\$552 ha^{-1}) and soybean (\$462 ha^{-1}) in the DT respectively averaged \$392 ha^{-1} and \$121 ha^{-1} more than similar crop sequences in the CT. Rotations increased cotton and soybean yields but not net returns because of the low value of the grain sorghum component. These data indicate that fall deep tillage should be incorporated into monocrop cotton and soybean crop sequences to maximize and stabilize net returns from these crops on Tunica clay.

Clayey soils occupy approximately 3.9 million ha or about 50% of the total land area of the lower Mississippi River alluvial flood plain (Pettiet, 1974). These soils are characterized by a high percentage of clay, slow internal drainage, and a high water-holding capacity.

The montmorillonitic clays exhibit a high degree of swelling and shrinking as the moisture content of the soil profile cycles between wet and dry. The clay fraction swells and severely restricts water movement into and through the soil profile when these soils approach the maximum water-holding capacity. As water is removed from the soils, the clay fraction shrinks and vertical cracks often form in the profile. When this occurs during the summer growing season, the roots of crops planted on these soils are damaged and often broken as the cracks widen over time.

These shrink–swell clay soils have mainly been planted to nonirrigated monocrop soybean. Soybean yields from this system of production are typically low (1300–1600 kg ha^{-1}) (Heatherly, 1983, 1988; Heatherly et al., 1990; Wesley and Cooke, 1988) and marginally profitable (Wesley and Cooke, 1988; Wesley et al., 1994a, 1994b, 1995). Cotton, grain sorghum, and rice (*Oryza sativa* L.) are also adapted to these soils, but they're planted on fewer hectares.

The use of large, heavy field equipment early in the season when the soil is wet may compact soil or reduce its productivity (Phillips and Kirkham, 1962; Gameda et al., 1987; Voorhees, 1985). When soil is compacted, its particles are rearranged such that the total pore space is decreased, whereas bulk density is increased (Singer and Munns, 1987). In most cases, the larger soil pores (macropores) are destroyed by the compactive force exerted on the soil, which results in reduced content and movement of air, water, heat and nutrients in the soil. Compaction also increases soil strength, thereby increasing the resistance to root penetration. When plant roots cannot explore the entire soil structure, plant nutrients become positionally unavailable.

Studies conducted by Akram and Kemper (1979) indicated that soil water content determined the degree of compaction for a given load. They described a positive correlation between soil water content and compaction. Larson et al. (1980) found that the bulk density increased linearly with soil clay content up to a content of 33%. They also determined that medium-textured soils with expanding-type clays compacted the most under high stress.

Deep tillage in the fall when the soil profile is dry disrupts the orientation of these soil blocks and reduces their size. It also increases the volume of loose soil material between these blocks, which improves infiltration by increasing the volume of macropores in the soil. Water moves more quickly through macropores than through the smaller pores in the soil blocks (Ritchie et al., 1972). Higher infiltration rates result in a larger volume of moistened soil following a rainfall event. Excess water is able to drain from the profile, which improves aeration of the soil and allows it to warm more quickly in the spring. Surface runoff and soil erosion are also reduced.

Deep tillage has increased the yields of numerous crops (Barbosa et al., 1989; Mathers et al., 1971), and it has proven to be a practical method for increasing water intake rates and depth-of-profile wetting of slowly permeable clays (Jensen and Sletten, 1965; Music et al., 1981). Recent research on a nonirrigated Tunica clay in Mississippi (Wesley and Smith, 1991) indicated that deep tillage in the fall when the upper profile was dry significantly reduced moisture tension levels during soybean reproductive stages R3 through R6 (Fehr and Caviness, 1977). Soybean yields from DTs averaged 2892 kg ha^{-1} and were significantly higher than the 1950 kg

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Abbreviations: CT, conventional-till production system; CV, coefficient of variation; DT, deep-till production system.

ha^{-1} yield from the CTs. Economic analyses of results from the same study indicated that net returns from the nonirrigated DT averaged \$182 ha^{-1} more than the average returns from the nonirrigated CT (\$119 ha^{-1}) and \$96 ha^{-1} more than the average returns from irrigated CT (\$205 ha^{-1}) (Wesley et al., 1993, 1994b).

Crop rotation is a process that also increases crop yields (Fahad et al., 1982; Baird and Benard, 1984; Boquet et al., 1986; Dabney et al., 1988). Biennial rotations of two summer crops often improves the yield of both crops. In the midwestern USA, a biennial rotation of corn (*Zea mays* L.) and soybean produced significant increases in the yields of both crops (Crookston and Kurle, 1989; Meese et al., 1991). A biennial rotation of soybean and grain sorghum has also been used effectively to enhance yields (Dabney et al., 1988; Peterson and Varvel, 1989; Roder et al., 1989a). The cause of the higher yields is related to either increased soil fertility, improved soil physical properties, improved weed control, or reduced incidences of disease, nematode, and insect pests.

Fahad et al. (1982) reported that continuous soybean cropping resulted in less water retention, lower cumulative water infiltration, and decreased soil aggregate stability compared with values measured under corn–soybean and grain sorghum–soybean rotational systems. Baird and Benard (1984) and Young et al. (1986) claim that crop rotations tend to control plant parasitic nematode populations, whereas Boquet et al. (1986) suggest that the reduction in disease is a vital factor. In corn–wheat (*Triticum aestivum* L.)–soybean and sorghum–wheat–soybean rotation sequences, crop yields were enhanced and johnsongrass [*Sorghum halapense* (L.) Pers.] was effectively controlled during the soybean sequence (Litsinger and Moody, 1976). Roder et al. (1989b) found that soybean root densities at most sample depths were greater when the previous crop was grain sorghum rather than soybean.

The objective of this study was to determine the individual and combined effects of fall deep tillage and crop rotations on yields and net returns from nonirrigated monocrop cotton, soybean, grain sorghum, and biennial rotations of cotton with grain sorghum and soybean with grain sorghum grown on the clayey soils of the lower Mississippi River alluvial flood plain. Grain sorghum was selected as the most desirable rotation crop because of its drought tolerance in nonirrigated crop production systems.

MATERIALS AND METHODS

General

Field studies were conducted from 1993 through 1997 on Tunica clay near Stoneville, MS. The surface layer of clay on Tunica clay ranges from 0.5 to 0.75 m thick and overlies a clay loam or silty clay loam subsoil. The soil of the A horizon (upper 0.75 m) at the test site was composed of 1% sand, 36% silt, and 63% clay while the B horizon was composed of 2% sand, 70% silt, and 28% clay. The field area for this study had a bulk density of approximately 1.4 g cm^{-3}.

The experiment was established in a split-plot design with a randomized complete block arrangement of treatments in four replicates each year. Whole plots were assigned to either a CT or a DT. Subplots consisted of crop sequences of continuous cotton, grain sorghum, and soybean and biennial rotations of cotton with grain sorghum and soybean with grain sorghum (Table 1). Each phase of each sequence was repeated each year, resulting in a total of seven crop sequences annually in each crop production system. Each subplot was 9.1 m wide and 30 m long and contained 12 bedded rows that were spaced 0.75 m apart. The designated crop rotation sequences were first grown in 1992; however, data from that year could not be used because the entire study area had been planted to monocrop soybean in 1991.

Table 1. Crop sequences for cotton (C), grain sorghum (GS), and soybean (S) grown in conventional (CT) and deep-till (DT) production systems on Tunica clay near Stoneville, MS from 1993–1997.

		Crop year				
Treatment	Crop sequence	1993	1994	1995	1996	1997
1	monocrop cotton	C	C	C	C	C
2	monocrop grain sorghum	GS	GS	GS	GS	GS
3	monocrop soybean	S	S	S	S	S
4	grain sorghum–cotton rotation	GS	C	GS	C	GS
5	cotton–grain sorghum rotation	C	GS	C	GS	C
6	grain sorghum–soybean rotation	GS	S	GS	S	GS
7	soybean–grain sorghum rotation	S	GS	S	GS	S

In this study, all CT and DT plots were prepared in the fall after the harvest of each respective crop. All DT plots were subsoiled annually to a depth of 0.4 m in the row direction under the center of each bed with parabolic chisels spaced 0.75 m apart. All deep tillage occurred between 9 September and 10 October each year. All CT and DT plots were bedded simultaneously with the same disk hipper to reshape the old beds. All beds were reshaped between 4 and 10 October each year and remained undisturbed throughout the winter season.

Crop rotation sequences used in the study spread field operations over a broader time frame than monocrop systems, and thus allowed timely and more efficient use of equipment. All crops were planted in April and May. Grain sorghum and soybean required minimum production inputs, whereas cotton required extensive inputs and timely application of numerous insecticides. Grain sorghum was harvested early in September, followed by soybean in mid-September. Cotton was harvested with a spindle picker from mid-September through early October.

Crop sequences were randomly assigned to subplots at the beginning of the test period and remained in the same location for the 5-yr study. All winter vegetation was eliminated from the subplots by a broadcast application of either paraquat [1, 1-dimethyl-4, 4-bipyridinium ion] or glyphosate [*N*-(phosphonomethyl)glycine] before planting each year. Approximately 30 d later, all subplots were smoothed with a row conditioner to prepare a suitable seedbed for planting. A brief summary of the production inputs and costs for each crop is presented below.

Cotton

Each year, cotton was planted at the rate of 11 kg ha^{-1} (120 000 seed ha^{-1}). 'DES-119' was planted in 1993, 1994, and 1995, and 'Suregrow 125' was planted in 1996 and 1997. Weeds were controlled with preemergence applications of metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl) acetamide] and fluometuron {*N*, *N*-dimethyl-*N*-[3-(trifluoromethyl)phenyl]urea}each year. Nitrogen was applied as a urea ammonium nitrate (UAN) solution in split applications beside each row. Nitrogen levels totaled 112, 112, 156, 180, and 200 kg ha $^{-1}$ from 1993 through 1997. Nitrogen levels in 1993 and 1994 were based on recommendations for cotton grown on sandy soils. However, the crop's appearance indicated that the N level was low, probably because of denitrification on the clayey soils. Therefore, N rates were adjusted upward in 1994, 1995, and 1996 to compensate for potential denitrification. Cultivation was used as needed. Postemergence herbicides were used in 1993, 1994, and 1997 for control of johnsongrass. Insecticides were applied each year as needed and as recommended by a crop consultant; applications ranged from as few as three in 1995 to as many as nine in 1993. Cotton was defoliated between 12 and 28 September and harvested between 26 September and 21 October each year. Six rows from each subplot were harvested with a plot picker for determination of seed cotton yields. Lint yields were calculated to be 35% of the harvested seed cotton yield, whereas cottonseed weight was calculated to be 60% of seed cotton yield. Total specified costs for monocrop cotton in the DT ranged from \$907 ha^{-1} in 1995 to \$1237 ha^{-1} in 1997 and averaged \$1024 ha^{-1} over the 5-yr study.

Soybean

Maturity Group V cultivars were planted each year and consisted of 'Pioneer 9592' from 1993 through 1995 and 'DPL-3588' in 1996 and 1997. Seeding rates were approximately 50 kg ha $^{-1}$ (325 000 seed ha^{-1}). Seed was treated with metalaxyl [*N*-(2, 6-dimetyl-phenyl)-*N*-(methoxy-acetyl)-DL-alanine methyl ester] each year. Metolachlor and metribuzin [4-amino-6-(1, 1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4H)-one] were applied as a preemergence tank mix each year, and cultivation was used as needed. Postemergence herbicides were applied in 1993, 1994, and 1995 for control of johnsongrass. Harvest dates ranged from 29 September to 5 October each year. Two subsamples, each consisting of five rows, were harvested with a plot combine from each subplot for yield determination. Soybean yields were reported at 130 g kg $^{-1}$ moisture. Total specified production costs for monocrop soybean in the DT ranged from \$285 ha^{-1} in 1996 to \$403 ha^{-1} in 1993 and averaged \$355 ha^{-1} over the 5-yr study.

Sorghum

'Pioneer 8333' grain sorghum was planted each year. Seeding rate was about 7.2 kg ha^{-1} (247 000 seed ha^{-1}). Metolachlor plus atrazine [6-chloro-*N*-ethyl-*N*^{1}-(1-methylethyl)-1,3,5-triazine-2,4-diamine] was applied at preemergence each year. All grain sorghum plots were fertilized with UAN at planting and at Growth Stage 2 (Vanderlip and Reeves, 1972), receiving a total of 180 kg ha^{-1} N each year. Two applications of dimethoate [phosphorodithioic acid O,O-dimethyl *S*-(2-(methylamino)-2-oxoethyl) ester] were used each year for control of sorghum midge [*Contarina sorghicola* (Coquillett)]. Harvest dates ranged from 29 September to 5 October each year. Two subsamples, each consisting of five rows, were harvested with a plot combine from each subplot for yield determinations. Sorghum yields were reported at 140 g kg^{-1} moisture. Total specified production costs for monocrop grain sorghum in the DT ranged from \$393 ha^{-1} in 1996 to \$485 ha^{-1} in 1993 and averaged \$444 ha^{-1} over the 5-yr study.

Economic Analyses

Crop enterprise budgets were developed annually for each crop sequence (Spurlock and Laughlin, 1992). Application rates for all of the variable inputs were those recommended and used for crop production in these experiments. Performance rates for all field operations were based on using eight-row equipment with associated power units. Crop prices used in the budgets were the market-year average prices reported by the Mississippi Agricultural Statistics Service (1993–1997). Gross income was calculated as the product of crop yield and market-year average price. Variable expenses were the actual prices paid by farmers each year and included the costs of fertilizer, herbicide, insecticides, seed, labor, fuel, repair and maintenance of equipment, and interest on operating capital. Fixed expenses included cost of tractors, self-propelled equipment, and implements. Annual depreciation was calculated using the straight-line method with zero salvage value. Annual interest charges were based on one-half of the original investment times a nominal interest rate on borrowed capital. Total specified expenses included both variable and fixed expenses. No charges were included in any budget for land, management, or general farm overhead. Net returns above specified expenses were calculated annually as the difference between gross income and total specified expenses. Average net returns from each crop sequence were calculated as the mean of the annual net returns over the 5-yr study.

The power complement included one tractor with 67 to 89 kW and one with 104 to 119 kW, one self-propelled combine with a 7.6-m header width, one 4-row cotton picker, and a high-clearance sprayer. The equipment complement included a stalk shredder, subsoiler, disk hipper, row conditioner, planter, liquid fertilizer applicator, cultivator, tractor-mounted sprayer, boll buggy, and a module builder. The farm enterprise size for the study was established to be 225 ha, based on the assumption that the subsoiler unit would be used 100 h each fall. Analysis of variance and LSD values were used each year and across years to determine the significant differences in the yields and net returns among crop production systems and crop sequences (SAS Inst., 1998).

RESULTS AND DISCUSSION

Weather

Growing-season precipitation exceeded the long-term average each year except 1997. However, the seasonal distribution of precipitation was erratic. In 1994, rainfall received in April, June, August, and September was 196 mm less than the long-term average, whereas record rainfall received within a 10-d period in July exceeded the long-term average by 201 mm. Less than average rainfall was received in August and September of 1994 and 1995. Rainfall received between July and September of 1997 was also less than the long-term average. For the 5-yr study, the monthly maximum air temperature ranged within ±3.3°C of the 30-yr normals.

Agronomic Performance

Cotton

In both the CT and DT, the average yield from monocrop cotton and cotton rotated with grain sorghum averaged the lowest in 1993 and the highest in 1997 (Table 2). The low yields in 1993 were partially attributed to the late planting date (17 May) and less than normal rainfall in June and July. The second lowest yields were produced in 1995 when all cotton plots were replanted on 8 May because of an unacceptable plant population due to excessive rainfall (244 mm) in April. However, rainfall deficits were also recorded in May, August, and

September of 1995, and thus adversely affected cotton yields.

Yields from crop sequences in the DT averaged higher than those in the CT every year. The yield advantage from the DT averaged 182 (P = 0.16), 308 (P = 0.02), 498 (P = 0.01), 1295 (P = 0.01), and 421 kg ha^{-1} (P = 0.01), respectively, from 1993 through 1997. Over the study, yields from cotton crop sequences in the DT averaged 541 kg ha^{-1} (P = 0.01) greater than yields from the same crop sequences in the CT (2184 kg ha^{-1}).

In the CT, yields from cotton rotated with grain sorghum were higher than yields from monocrop cotton in all years. This yield increase attributed to rotation effects averaged 710 (P = 0.01), 19 (P = 0.91), 974 (P = 0.01), 429 (P = 0.01), and 1273 kg ha^{-1} (P = 0.01), respectively, from 1993 through 1997. Over the 5-yr study, yields from the cotton–grain sorghum rotation in the CT averaged 681 kg ha^{-1} (P = 0.01) greater than yields from monocrop cotton in the CT (1844 kg ha^{-1}). In the DT, yields from the same crop sequences indicate that the cotton rotation increased yields 384 kg ha^{-1} (P = 0.03) in 1993, 425 kg ha^{-1} (P = 0.01) in 1995, 68 kg ha^{-1} (P = 0.68) in 1996, and 301 kg ha^{-1} (P = 0.07) in 1997. Over the study, yields from cotton rotated with grain sorghum rotation averaged 187 kg ha^{-1} (P = 0.20) greater than yields from monocrop cotton in the DT (2632 kg ha^{-1}). However, this yield increase was over and above the higher yield from monocrop cotton in the DT.

Yield data from the DT indicate that fall deep tillage increased the yield of monocrop cotton in all years. These yield increases from 1993 through 1997 averaged 345 (P = 0.06), 438 (P = 0.02), 773 (P = 0.01), 1475 (P = 0.01), and 907 kg ha^{-1} (P = 0.01), respectively. Over the study, yields from monocrop cotton in the DT averaged 788 kg ha^{-1} (P = 0.01) greater than those in the CT (1844 kg ha^{-1}). This 788 kg ha^{-1} increase attributed to deep tillage was greater than the increase from rotation in the CT (681 kg ha^{-1}) and DT (187 kg ha^{-1}). Over the study, yields from monocrop cotton in the DT averaged 107 kg ha^{-1} greater than yields from rotated cotton in the CT (2525 kg ha^{-1}). Yields from rotated cotton in the CT and DT were virtually the same each year, except in 1996 when yields from rotated cotton in the DT exceeded those from the CT by 1114 kg ha^{-1} (P = 0.01). Over the study, yields from rotated cotton in the DT averaged 294 kg ha^{-1} (P = 0.05) greater than yields from rotated cotton in the CT (2525 kg ha^{-1}).

The combined effect of fall deep tillage and crop rotation is indicated by comparing yields from cotton rotation in the DT with yields from monocrop cotton in the CT. Yields from cotton rotation in the DT were greater in all years, exceeding monocrop cotton yields in the CT by an average of 729 (P = 0.01), 196 (P = 0.26), 1198 (P = 0.01), 1543 (P = 0.01), and 1208 kg ha^{-1} (P = 0.01) from 1993 through 1997. Over the study, the combined effects of deep tillage and rotation increased the average yield from cotton to 975 kg ha^{-1} (P = 0.01) above yields from moncrop cotton in the CT (1844 kg ha^{-1}).

Soybean

In the CT and DT, yields from soybean in the monocrop and rotated systems averaged the lowest in 1993 and the highest in 1997 (Table 3). Yields from soybean crop sequences in the DT were greater than those from the CT in all years. Yields from the DT exceeded yields from the CT by an average of 526 (P = 0.09), 546 (P = 0.08), 689 (P = 0.03), 461 (P = 0.14), and 403 kg ha^{-1} (P = 0.19) from 1993 through 1997. These yield increases in the DT occurred in spite of the severe moisture deficits in August and September of 1994 and 1995 during the R5 and R6 stages of seed development. Over the study, yields from soybean crop sequences in the DT averaged 525 kg ha^{-1} (P = 0.07) greater than yields from crop sequences in the CT (2983 kg ha^{-1}).

In the CT and DT, soybean yields from the grain sorghum rotation were greater than respective monocrop yields in all years. However, these differences were

Table 2. Yield of seed cotton grown in conventional-till (CT) and deep-till (DT) production systems on Tunica clay near Stoneville, MS from 1993–1997.

Production system	Treatment†	Crop year 1993	1994	1995	1996	1997	Avg.
		kg ha^{-1}					
CT	1	1253	2655	1310	1702	2300	1844
	4	–	2674	–	2131	–	
	5	1963	–	2284	–	3573	2525
	Avg.	1608	2664	1797	1916	2936	2184
DT	1	1598	3093	2083	3177	3207	2632
	4	–	2851	–	3245		
	5	1982	–	2508	–	3508	2819
	Avg.	1790	2972	2295	3211	3357	2725
LSD (0.05)‡	271	NS	*	*	*	*	248*
LSD (0.05)§	352	*	NS	*	*	*	316*
LSD (0.05)¶	351	*	*	*	*	*	298*

* Significant at the 0.05 probability level.
† Treatment: 1, monocrop cotton; 4, grain sorghum–cotton rotation; 5, cotton–grain sorghum rotation.
‡ For comparison of production system means.
§ For comparison of means within production systems.
¶ For comparison of means across production systems.

Table 3. Grain yield of soybean grown in conventional-till (CT) and deep-till (DT) production systems on Tunica clay near Stoneville, MS from 1993–1997.

Production system	Treatment†	Crop year 1993	1994	1995	1996	1997	Avg.
		kg ha^{-1}					
CT	3	2184	2962	2418	3048	3377	2798
	6	–	3135	–	3253	–	
	7	2812	–	2775	–	3872	3169
	Avg.	2498	3048	2596	3150	3624	2983
DT	3	2815	3448	3198	3525	3951	3387
	6	–	3741	–	3698	–	
	7	3234	–	3373	–	4104	3630
	Avg.	3024	3594	3285	3611	4027	3508
LSD (0.05)‡	643	NS	NS	*	NS	NS	598 NS
LSD (0.05)§	555	*	NS	NS	NS	NS	508 NS
LSD (0.05)¶	723	*	*	*	NS	*	637*

* Significant at the 0.05 probability level.
† Treatment: 3, monocrop soybean; 6, grain sorghum–soybean rotation; 7, soybean–grain sorghum rotation.
‡ For comparison of production system means.
§ For comparison of means within production systems.
¶ For comparison of means across production systems.

relatively small, except in 1993 and 1997 when yields from soybean rotations in the CT respectively averaged 628 ($P = 0.02$) and 495 kg ha^{-1} ($P = 0.07$) greater than monocrop yields. Over the study, the yields from rotated soybean respectively averaged 371 kg ha^{-1} ($P = 0.12$) greater than the yields from monocrop soybean in the CT (2798 kg ha^{-1}) and 243 kg ha^{-1} ($P = 0.28$) greater than monocrop soybean in the DT (3387 kg ha^{-1}).

The yield response to fall deep tillage was consistent and similar for monocrop soybean and for soybean rotated with grain sorghum. Yields from monocrop soybean in the DT exceeded those from monocrop soybean in the CT by an average of 631 ($P = 0.07$), 486 ($P = 0.15$), 780 ($P = 0.03$), 477 ($P = 0.16$), and 574 kg ha^{-1} ($P = 0.09$) from 1993 through 1997. Yields from rotated soybean in DT exceeded those in the CT by an average of 422 ($P = 0.21$), 606 ($P = 0.08$), 598 ($P = 0.08$), 445 ($P = 0.19$), and 232 kg ha^{-1} ($P = 0.49$) from 1993 through 1997. Over the study, yield from monocrop soybean in the DT averaged 589 kg ha^{-1} ($P = 0.06$) greater than that in the CT (2798 kg ha^{-1}) while soybean rotated with grain sorghum in the DT averaged 461 kg ha^{-1} ($P = 0.13$) greater than that in the CT (3169 kg ha^{-1}). As with cotton, the 589 kg ha^{-1} yield increase attributed to deep tillage of monocrop soybean was greater than the increase from the rotation in the CT (371 kg ha^{-1}) and DT (243 kg ha^{-1}). Over the study, yields from monocrop soybean in the DT averaged 218 kg ha^{-1} greater than those from rotated soybean in CT (3169 kg ha^{-1}).

The combined effect of deep tillage and crop rotation increased soybean yields above monocrop soybean yields in the CT in all years. Yields of rotated soybean in the DT exceeded monocrop CT yields by 1050 ($P = 0.01$), 779 ($P = 0.03$), 955 ($P = 0.01$), 650 ($P = 0.07$), and 727 kg ha^{-1} ($P = 0.05$) from 1993 through 1997. Over the study, the combined effect of deep tillage and crop rotation in the DT increased the average yield to 832 kg ha^{-1} ($P = 0.01$) above the average yield from monocrop soybean in the CT (2798 kg ha^{-1}).

Sorghum

Yield of monocrop grain sorghum declined in both production systems over time (Table 4). However, the decline was less in the DT. An increased infestation with johnsongrass that became troublesome over time was noted in monocrop grain-sorghum sequences in both the CT and DT. However, the infestation seemed to be less severe in the DT. This could be due to subsoiling in the fall that exposed more rhizomes to the soil surface and allowed better control of this perennial weed, which is closely related to grain sorghum. Johnsongrass is a major problem for grain sorghum production in the midsouthern USA; therefore, grain sorghum is only produced on a rotational basis to allow for johnsongrass control in the nonsorghum crop year.

Average yields from grain sorghum crop sequences in the CT and DT were similar in all years except 1997. The higher yield from the sorghum crop sequences in the DT in 1997 was attributed to a combination of above-normal sorghum yields from the cotton (7382 kg ha^{-1}) and soybean (7373 kg ha^{-1}) rotations in the DT and extremely low yields from monocrop sorghum (3661 kg ha^{-1}) in the CT caused by severe johnsongrass infestation. The combined effect of deep tillage and crop rotation virtually eliminated the competitiveness of johnsongrass that occurred in monocrop sorghum in the CT. However, over the study, average yields from grain sorghum crop sequences in the CT and DT were similar.

In the CT, yields from grain sorghum in the cotton rotation exceeded monocrop sorghum yields by 1344 kg ha^{-1} ($P = 0.01$) in 1994, 899 kg ha^{-1} ($P = 0.05$) in 1995, 2182 kg ha^{-1} ($P = 0.01$) in 1997, and 898 kg ha^{-1} ($P = 0.01$) over the study. Rotation of grain sorghum with soybean increased grain sorghum yields by 3128 kg ha^{-1} ($P = 0.01$) in 1997 and 840 kg ha^{-1} ($P = 0.01$) over the study. In the DT, rotations of grain sorghum with cotton and with soybean increased grain sorghum yields above monocrop yields in all years. Yield increases from the cotton rotation ranged from 329 kg ha^{-1} ($P = 0.47$) in 1993 to 2654 kg ha^{-1} ($P = 0.01$) in 1997 and averaged 1047 kg ha^{-1} ($P = 0.01$) over the study. Similarly, yield increases from the soybean rotation ranged from 372 kg ha^{-1} ($P = 0.42$) in 1993 to 2645 kg ha^{-1} ($P = 0.01$) in 1997 and averaged 1068 kg ha^{-1} ($P = 0.01$) over the study.

Yields from monocrop sorghum in the DT were greater than those in the CT each year and averaged 561 kg ha^{-1} ($P = 0.22$) greater over the study. Yields from sorghum in the cotton and soybean rotations in the DT were also greater than respective rotated yields in the CT each year, except in the cotton rotation in 1994. Over the study, yields from sorghum in the cotton and soybean rotations in the DT respectively averaged 710 kg ha^{-1} ($P = 0.13$) and 789 kg ha^{-1} ($P = 0.09$) greater than those in the CT.

The combined effects of fall deep tillage and crop

Table 4. Grain yield of sorghum grown in conventional-till (CT) and deep-till (DT) production systems on Tunica clay near Stoneville, MS from 1993–1997.

Production system	Treatment†	Crop year					
		1993	1994	1995	1996	1997	Avg.
		kg ha^{-1}					
CT	2	5706	5213	4643	4381	3661	4721
	4	5700	–	5542	–	5843	5619
	5	–	6557	–	4455	–	
	6	5736	–	5289	–	6789	5561
	7	–	6080	–	3910	–	
	Avg.	5714	5950	5158	4249	5431	5300
DT	2	6093	5893	5112	4585	4728	5282
	4	6422	–	6334	–	7382	6329
	5	–	6490	–	5018	–	
	6	6465	–	6155	–	7373	6350
	7	–	6702	–	5054	–	
	Avg.	6327	6362	5867	4886	6494	5987
LSD (0.05)‡	1009	NS	NS	NS	NS	*	923 NS
LSD (0.05)§	917	NS	*	*	NS	*	571*
LSD (0.05)¶	1220	NS	*	*	NS	*	966*

* Significant at the 0.05 probability level.
† Treatment: 2, monocrop grain sorghum; 4, grain sorghum–cotton rotation; 5, cotton–grain sorghum rotation; 6, grain sorghum–soybean rotation; 7, soybean–grain sorghum rotation.
‡ For comparison of production system means.
§ For comparison of means within production systems.
¶ For comparison of means across production systems.

rotations resulted in the greatest yield increase above the yield from monocrop grain sorghum in the CT. Over the study, yields from grain sorghum in both the cotton and soybean rotations in the DT respectively averaged 1608 kg ha^{-1} (P = 0.01) and 1629 kg ha^{-1} (P = 0.01) greater than those from monocrop grain sorghum in the CT.

Economic Performance

General

Yield data (Tables 2, 3, and 4) along with the market-year average prices were used to provide a basis for economic evaluations. The market-year average prices for cotton lint for crop years 1993 through 1997 were \$1.28, \$1.59, \$1.61, \$1.50, and \$1.54 kg^{-1} respectively, whereas cottonseed prices were \$0.11 kg^{-1} in all years. Market-year prices for soybean were \$0.2425, \$0.2058, \$0.2499, \$0.2620, and \$0.2495 kg^{-1} respectively, whereas prices for grain sorghum were \$0.0882, \$0.0839, \$0.1059, \$0.1201, and \$0.0996 kg^{-1}, respectively. Gross income, total specified expenses, and net returns above specified expenses were calculated for each crop sequence each year. However, only net returns are presented and discussed.

Cotton

Net returns from cotton crop sequences in the DT averaged higher than those in the CT for all years (Table 5). The low yield in 1993, in conjunction with a low price for cotton lint (\$1.28 kg^{-1}), resulted in a negative net return from monocrop cotton in the CT (−\$278 ha^{-1}) and DT (−\$143 ha^{-1}). Net returns from rotated cotton in both production systems in 1993 were positive because of the higher cotton yields from the rotations. However, these small returns were not sufficient to offset the larger negative returns from monocrop cotton, and thus resulted in negative net returns in both production systems. The average net returns from each production system were positive in all other years because of higher yields and higher crop prices. Over the study, net returns from cotton crop sequences in the DT (\$598 ha^{-1}) averaged \$263 ha^{-1} (P = 0.01) more than similar crop sequences in the CT (\$335 ha^{-1}).

In the CT and DT, net returns from cotton rotated with grain sorghum were higher than net returns from monocrop cotton in all years except 1994, when monocrop and rotated cotton yields were similar. In the CT, net returns from cotton rotated with grain sorghum averaged \$350 ha^{-1} (P = 0.01) more than from monocrop cotton (\$160 ha^{-1}). In the DT, the increases from rotation effects were less than the increases in the CT because of the higher overall yields and net returns from monocrop cotton in the DT. Net returns from the rotation in DT averaged \$93 ha^{-1} (P = 0.27) more than the net returns from monocrop cotton in DT (\$552 ha^{-1}).

Fall deep tillage increased net returns from monocrop cotton in all years. These increases from 1993 through 1997 averaged \$135 (P = 0.18), \$221 (P = 0.04), \$406 (P = 0.01), \$735 (P = 0.01), and \$462 ha^{-1} (P = 0.01) more than returns from monocrop cotton in the CT (\$160 ha^{-1}), and over the study they averaged \$392 ha^{-1} (P = 0.01) more. In fact, net returns from monocrop cotton in the DT (\$552 ha^{-1}) averaged \$42 ha^{-1} more than returns from rotated cotton in the CT (\$510 ha^{-1}).

The combined effect of deep tillage and rotation resulted in net returns that averaged higher than returns from monocrop cotton in the CT for all years. These net returns averaged \$303 (P = 0.01), \$90 (P = 0.37), \$641 (P = 0.01), \$770 (P = 0.01), and \$621 ha^{-1} (P = 0.01) from 1993 through 1997 and \$485 ha^{-1} (P = 0.01) over the study.

Soybean

Net returns from soybean crop sequences in the DT averaged higher than net returns from soybean crop sequences in the CT for all years (Table 6). Net returns

Table 5. Net returns above specified costs for cotton lint and cottonseed grown in conventional-till (CT) and deep-till (DT) production systems on Tunica clay near Stoneville, MS from 1993–1997.

Production system	Treatment†	Crop year 1993	1994	1995	1996	1997	Avg.
		$ ha^{-1}					
CT	1	−278	676	−1	156	247	160
	4	–	686	–	377	–	
	5	32	–	537	–	920	510
	Avg.	−123	681	268	266	583	335
DT	1	−143	897	405	891	709	552
	4	–	766	–	926	–	
	5	25	–	640	–	868	645
	Avg.	−59	831	522	908	788	598
LSD (0.05)‡	155	NS	*	*	*	*	142*
LSD (0.05)§	207	*	NS	*	*	*	187*
LSD (0.05)¶	204	*	*	*	*	*	173*

* Significant at the 0.05 probability level.
† Treatment: 1, monocrop cotton; 4, grain sorghum–cotton rotation; 5, cotton–grain sorghum rotation.
‡ For comparison of production system means.
§ For comparison of means within production systems.
¶ For comparison of means across production systems.

Table 6. Net returns above specified costs for soybeans grown in conventional-till (CT) and deep-till (DT) production systems on Tunica clay near Stoneville, MS from 1993–1997.

Production system	Treatment†	Crop year 1993	1994	1995	1996	1997	Avg.
		$ ha^{-1}					
CT	3	146	275	261	525	497	341
	6	–	309	–	577	–	
	7	295	–	348	–	606	427
	Avg.	220	292	304	551	551	384
DT	3	280	356	430	624	618	462
	6	–	414	–	668	–	
	7	379	–	473	–	644	516
	Avg.	329	385	451	646	631	489
LSD (0.05)‡	148	NS	NS	*	NS	NS	138 NS
LSD (0.05)§	132	*	NS	NS	NS	NS	121 NS
LSD (0.05)¶	168	*	NS	*	NS	NS	148*

* Significant at the 0.05 probability level.
† Treatment: 3, monocrop soybean; 6, grain sorghum–soybean rotation; 7, soybean–grain sorghum rotation.
‡ For comparison of production system means.
§ For comparison of means within production systems.
¶ For comparison of means across production systems.

from soybean in the DT exceeded those from the CT by \$109 ($P = 0.13$), \$93 ($P = 0.20$), \$147 ($P = 0.05$), \$95 ($P = 0.18$), and \$80 ha^{-1} ($P = 0.26$) from 1993 through 1997. When averaged across all years, net returns from soybean crop sequences in the DT were \$105 ha^{-1} ($P = 0.10$) more than those in the CT (\$384 ha^{-1}).

In the CT and DT, net returns from rotated soybean were higher than returns from monocrop soybean in all years. In the CT, net returns ranged from \$34 ha^{-1} ($P = 0.57$) more than net returns from monocrop soybean in 1994 to \$149 ha^{-1} ($P = 0.02$) more in 1993, averaging \$86 ha^{-1} ($P = 0.13$) more over the study. In the DT, the increase ranged from \$26 ha^{-1} ($P = 0.67$) more than net returns from monocrop soybean in 1997 to \$99 ha^{-1} ($P = 0.12$) more in 1993, averaging \$54 ha^{-1} ($P = 0.31$) over the study. The additional net returns (\$54 ha^{-1}) were attributed to rotation effects and were over and above the higher returns from monocrop soybean in the DT.

Net returns from monocrop soybean in the DT exceeded those in the CT each year and over the study. These higher returns from the DT averaged \$134 ($P = 0.09$), \$81 ($P = 0.30$), \$169 ($P = 0.05$), \$99 ($P = 0.21$), and \$121 ha^{-1} ($P = 0.13$) from 1993 through 1997 and \$121 ha^{-1} ($P = 0.09$) over the study. Net returns from monocrop soybean in the DT averaged \$35 ha^{-1} more than net returns from the soybean rotation in the CT (\$427 ha^{-1}).

The combined effect of fall deep tillage and crop rotation produced net returns that averaged higher than returns from monocrop soybean in the CT for all years. These returns ranged from \$139 ha^{-1} ($P = 0.10$) more in 1994 to \$233 ha^{-1} ($P = 0.01$) more in 1993. Over the study, the combined effect of deep tillage and rotation increased net returns \$175 ha^{-1} ($P = 0.02$) above the returns from monocrop soybean in CT (\$341 ha^{-1}).

Sorghum

Net returns from grain sorghum grown in crop sequences in the DT averaged higher than returns from similar crop sequences in the CT for all years (Table 7). These increases were small and ranged from \$15 ha^{-1} ($P = 0.72$) in 1994 to \$81 ha^{-1} ($P = 0.08$) in 1997 and averaged \$46 ha^{-1} over the study.

In the CT, net returns from grain sorghum grown in the cotton rotation were greater than net returns from monocrop grain sorghum in all years except 1993, whereas net returns from grain sorghum in the soybean rotation were greater than returns from monocrop grain sorghum in all years except 1996. Over the study, net returns from grain sorghum grown in the cotton and soybean rotations in the CT respectively averaged \$86 ($P = 0.01$) and \$81 ha^{-1} ($P = 0.01$) more than returns from monocrop grain sorghum in the CT (\$39 ha^{-1}). In the DT, net returns from grain sorghum in the cotton and soybean rotations were greater than net returns from monocrop grain sorghum in all years. Net returns from grain sorghum grown in the cotton and soybean rotations in the DT were virtually the same each year, averaging \$103 ($P = 0.01$) and \$106 ha^{-1} ($P = 0.01$) more than returns from monocrop grain sorghum in the DT (\$71 ha^{-1}) over the study.

Table 7. Net returns above specified costs for grain sorghum grown in conventional-till (CT) and deep-till (DT) production systems on Tunica clay near Stoneville, MS from 1993–1997.

Production system	Treatment†	Crop year					
		1993	1994	1995	1996	1997	Avg.
		$ ha^{-1}					
CT	2	36	27	59	138	−66	39
	4	35	–	149	–	138	125
	5	–	131	–	170	–	
	6	38	–	123	–	238	120
	7	–	94	–	108	–	
	Avg.	36	84	110	139	103	95
DT	2	52	63	85	138	15	71
	4	79	–	206	–	263	174
	5	–	109	–	211	–	
	6	82	–	189	–	273	177
	7	–	125	–	215	–	
	Avg.	71	99	160	188	184	141
LSD (0.05)‡	92	NS	NS	NS	NS	NS	85 NS
LSD (0.05)§	85	NS	*	*	NS	*	52*
LSD (0.05)¶	112	NS	NS	*	NS	*	89*

* Significant at the 0.05 probability level.

† Treatment: 2, monocrop grain sorghum; 4, grain sorghum–cotton rotation; 5, cotton–grain sorghum rotation; 6, grain sorghum–soybean rotation; 7, soybean–grain sorghum rotation.

‡ For comparison of production system means.

§ For comparison of means within production systems.

¶ For comparison of means across production systems.

Net returns from each grain sorghum crop sequence in the DT were greater than returns from comparable crop sequences in the CT for all years except 1994. Over the study, net returns from sorghum grown in the cotton and soybean crop sequences in the DT respectively averaged \$49 ($P = 0.24$) and \$57 ha^{-1} ($P = 0.18$) more than returns from comparable crop sequences in the CT.

The combined effect of deep tillage and crop rotation is reflected in the higher net returns from grain sorghum in both rotations in the DT relative to monocrop grain sorghum in the CT for all years. Net returns from grain sorghum in the cotton rotation ranged from \$43 ha^{-1} ($P = 0.44$) in 1993 to \$329 ha^{-1} ($P = 0.01$) in 1997 and \$46 ha^{-1} ($P = 0.40$) in 1993 to \$339 ha^{-1} ($P = 0.01$) in 1997 for the soybean rotation. Over the study, net returns from grain sorghum in the cotton and soybean rotations in the DT respectively averaged \$135 ($P = 0.01$) and \$138 ha^{-1} ($P = 0.01$) more than monocrop grain sorghum in the CT (\$39 ha^{-1}).

Economic Summary

General

Data in Table 8 presents annual net returns, overall net returns, and a measure of stability for each crop sequence in the CT and DT. For example, net returns from cotton and sorghum grown in the cotton–sorghum rotation in the CT respectively averaged \$510 (Table 5) and \$125 ha^{-1} (Table 7). When combined over the study, they averaged \$318 ha^{-1} with a coefficient of variation (CV) of 58% (Table 8). A summary of these relationships for each cotton and soybean crop sequence in the CT and DT is discussed below.

Table 8. Avg. net returns above specified production costs and stability of net returns for crop sequences grown in conventional-till (CT) and deep-till (DT) production systems on Tunica clay near Stoneville, MS from 1993–1997.

Production system	Treatment†	Crop year 1993	1994	1995	1996	1997	Stability§ Mean‡	Std. Dev.	CV
		$ ha^{-1}							%
CT	1	−278	646	−1	156	247	160	350	219
	2	36	27	59	138	−66	39	73	187
	3	146	275	261	525	497	341	164	48
	4	35	686	149	377	138	277	261	94
	5	32	131	537	170	920	358	368	103
	Avg.	34	409	343	274	529	318	184	58
	6	38	309	123	577	238	257	207	81
	7	295	94	348	108	606	290	209	72
	Avg.	167	202	236	343	422	274	106	39
DT	1	−143	897	405	891	709	552	436	79
	2	52	63	85	138	15	71	22	31
	3	280	356	430	624	618	462	155	34
	4	79	766	206	926	263	448	374	84
	5	25	109	640	211	868	371	365	98
	Avg.	52	438	423	568	566	409	211	52
	6	82	414	189	668	273	325	227	70
	7	379	125	473	215	644	367	206	56
	Avg.	231	270	331	441	458	346	101	29

† Treatment: 1, monocrop cotton; 2, monocrop grain sorghum; 3, monocrop soybean; 4, grain sorghum–cotton rotation; 5, cotton–grain sorghum rotation; 6, grain sorghum–soybean rotation; 7, soybean–grain sorghum rotation.
‡ Overall mean of designated crop sequence.
§ Stability of net returns across years is measured as the coefficient of variation (CV) of yearly variance relative to overall mean.

Cotton

Net returns from monocrop cotton in the CT averaged \$160 ha^{-1} over the 5-yr study and were highly variable across years, with a CV of 219% (Table 8). Net returns from the cotton–grain sorghum rotation in the CT averaged \$318 ha^{-1}. Thus in the CT, net returns from the cotton–grain sorghum rotation averaged \$158 ha^{-1} (P = 0.01) more and were more stable (CV = 58) than returns from monocrop cotton (\$160 ha^{-1}). In the DT, returns from the cotton–grain sorghum rotation averaged \$409 ha^{-1}, which was \$249 ha^{-1} (P = 0.01) more and also more stable (CV = 52) than returns from monocrop cotton in the CT. However, net returns from monocrop cotton in the DT averaged \$552 ha^{-1}, were relatively stable (CV = 79), and were greater than returns from all other cotton crop sequences. Net returns from monocrop cotton in the DT averaged \$392 ha^{-1} (P = 0.01) more than those in the CT, \$234 ha^{-1} (P = 0.01) more than returns from rotated cotton in the CT, and \$143 ha^{-1} (P = 0.01) more than returns from rotated cotton in the DT.

Soybean

Net returns from monocrop soybean grown in the CT were relatively stable (CV = 48), averaged \$341 ha^{-1} (Table 8), and were similar to net returns from the soybean–grain sorghum rotation in the CT (\$274 ha^{-1}) and DT (\$346 ha^{-1}). However, variations in returns across years for the soybean–sorghum rotations in the CT (CV = 39) and DT (CV = 29) were among the lowest. As with cotton, net returns from monocrop soybean in the DT were stable across years (CV = 34), averaged \$462 ha^{-1}, and were greater than net returns from all other soybean crop sequences. Net returns from monocrop soybean in the DT averaged \$121 ha^{-1} (P = 0.10) more than returns from monocrop soybean in the CT, \$188 ha^{-1} (P = 0.01) more than returns from the soybean rotation in the CT, and \$116 ha^{-1} (P = 0.03) more than returns from the soybean rotation in the DT.

CONCLUSIONS

Net returns from all crop sequences in the DT were higher and more stable than comparable crop sequences in the CT. Fall deep tillage increased the net returns by \$392 ha^{-1} for monocrop cotton, \$121 ha^{-1} for monocrop soybean, \$91 ha^{-1} for cotton–grain sorghum rotation, \$72 ha^{-1} for soybean–grain sorghum rotation, and \$32 ha^{-1} for monocrop grain sorghum. However, net returns from monocrop grain sorghum in both production systems were not sufficient to cover land rental costs (Mississippi Agricultural Statistics Service, 1993–1997).

These data clearly indicate that fall deep tillage should be incorporated into crop sequences on clayey soils to maximize and stabilize net returns from cotton and soybean. Data also show that biennial rotations of cotton and soybean with grain sorghum in the CT and DT increased yields and net returns from the cotton and soybean components in the rotations. However, the average net returns from the cotton and soybean rotation sequences in the CT and the soybean rotation sequence in the DT were significantly lower than returns from either monocrop cotton or monocrop soybean in the DT. This was because of the extremely low net returns from the grain sorghum component grown in alternate years in the rotations. Thus, the recommendation for Midsouth producers would be deep tillage of Tunica clay and similar soils in the fall, with production of monocrop cotton or soybean the following crop production season. Rotations with grain sorghum should be considered only if a significant improvement in price occurs for grain sorghum or after a need develops for rotations, such as disease, weed pressure, or government program limitations.

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